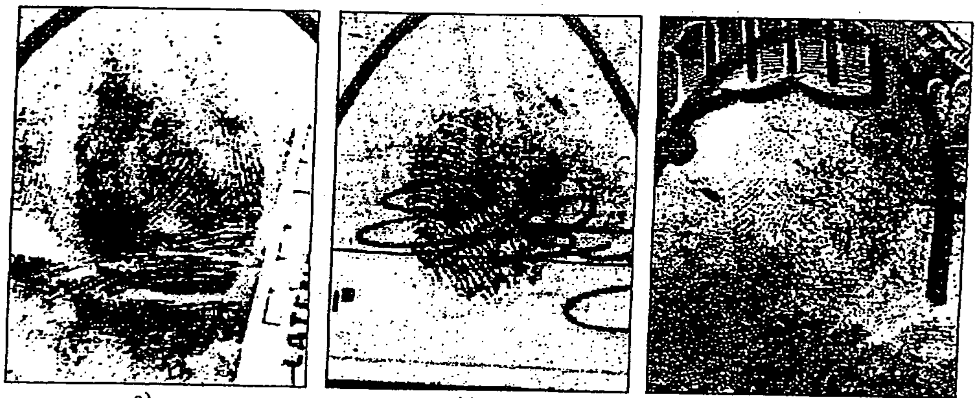
chemical reagents, instruments, and systematic approaches involving a combination of methods (Lee and Gaensslen, 2001).



a) b) c)

Figure 2.5. Examples of a) good, b) bad, and c) ugly latent fingerprints from NIST Special Database 27 (Garris and McCabe, 2000).

2.4 Live-scan Fingerprint Sensing

The most important part of a fingerprint scanner is the sensor (or sensing element), which is the component where the fingerprint image is formed. Almost all the existing sensors belong to one of the three families: optical, solid-state, and ultrasound.

Optical sensors

- *Frustrated Total Internal Reflection (FTIR)*: This is the oldest and most used live-scan acquisition technique today (Hase and Shimisu (1984) and Bahuguna and Corboline (1996)). The finger touches the top side of a glass prism, but while the ridges enter in contact with the prism surface, the valleys remain at a certain distance (see Figure 2.6); the left side of the prism is illuminated through a diffused light (a bank of light-emitting diodes (LED) or a film planar light). The light entering the prism is reflected at the valleys, and randomly scattered (absorbed) at the ridges. The lack of reflection allows the ridges (which appear dark in the image) to be discriminated from the valleys (appearing bright). The light rays exit from the right side of the prism and

are focused through a lens onto a CCD or CMOS image sensor. Because FTIR devices sense a three-dimensional surface, they cannot be easily deceived by presentation of a photograph or printed image of a fingerprint.

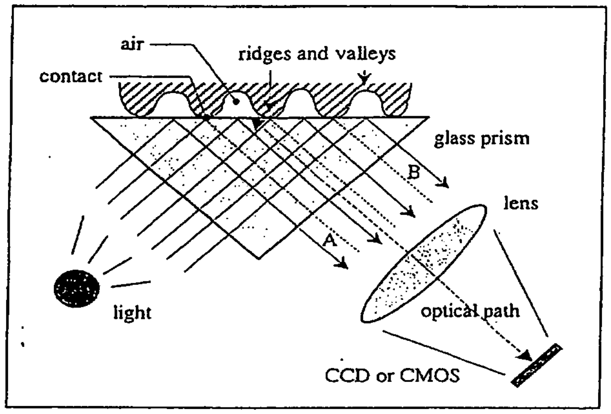


Figure 2.6. FTIR-based fingerprint sensing.

A simple optical device like that shown in Figure 2.6 introduces geometrical distortions. The most evident one is known as trapezoidal distortion; an example is shown in Figure 2.6. Since the fingerprint plane is not parallel to the CCD plane, rays A and B have different lengths, and this results in a stretching or compression of the image regions which is a function of their distance from the optical axis. Compensation for this distortion may be optics-based (by using ad hoc pre-molded plastic lenses or holograms as proposed by Seigo, Shin, and Takashi (1989) and Igaki et al. (1992)) or software-based (calibration techniques).

When a finger is very dry, it does not make uniform contact with the sensor surface. To improve the formation of fingerprints from dry fingers, whose ridges do not contain sweat particles, some scanner producers use silicone coating, which favors the contact of the skin with the prism. With the aim of reducing the cost of the optical devices, plastic is nowadays often used instead of glass for prisms and lenses, and CMOS cameras are mounted instead of more expensive CCDs.

In spite of a generally better image quality and the possibility of larger sensing areas, FTIR-based devices cannot be miniaturized unlike other optical techniques (e.g., optical fibers) or solid-state devices. In fact, the length of the optical path (i.e., the distance between the prism external surface and the image sensor) cannot be significantly reduced without introducing severe optical distortion at the image edges; using one or more intermediate mirrors may help in assembling working solutions in rea-

sonably small packages, but even if these are suitable for embedding into a mouse or a keyboard, they are still too large to be integrated into a PDA or a mobile phone.

- *FTIR with a sheet prism*: Using a sheet prism made of a number of "prismlets" adjacent to each other (see Figure 2.7), instead of a single large prism, allows the size of the mechanical assembly to be reduced to some extent (Chen and Kuo (1995), Zhou, Qiao, and Mok (1998) and Xia and O'Gorman (2003)): in fact, even if the optical path remains the same, the sheet prism is nearly flat. However, the quality of the acquired images is generally lower than traditional FTIR techniques using glass prisms.

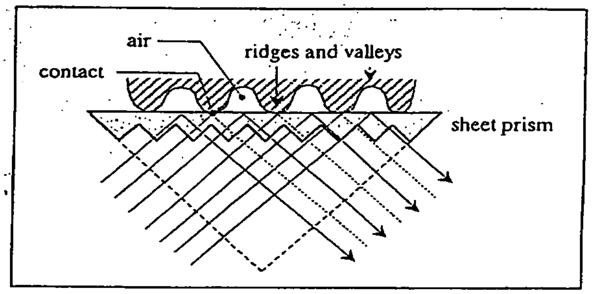


Figure 2.7. The use of a sheet prism in FTIR fingerprint acquisition.

- *Optical fibers*: A significant reduction of the packaging size can be achieved by substituting prism and lens with a fiber-optic platen (Fujieda, Ono, and Sugama (1995) and Dowling and Knowlton (1988)). The finger is in direct contact with the upper side of the platen; on the opposite side, a CCD or CMOS, tightly coupled with the platen, receives the finger residual light conveyed through the glass fibers (see Figure 2.8). Unlike the FTIR devices, here the CCD/CMOS is in direct contact with the platen (without any intermediate lens), and therefore its size has to cover the whole sensing area. This may result in a high cost for producing large area sensors.

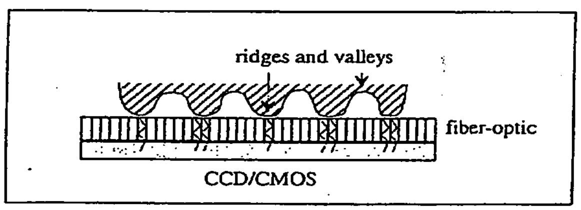


Figure 2.8. A sensor based on optical fibers. Residual light emitted by the finger is conveyed through micro-optical guides to the array of pixels that constitute the CCD/CMOS.

- *Electro-optical*: These devices are constituted of two main layers; the first layer contains a polymer that, when polarized with the proper voltage, emits light that depends on the potential applied on one side (see Figure 2.9). As ridges touch the polymer and the valleys do not, the potential is not the same across the surface when a finger is placed on it and the amount of light emitted varies, thus allowing a luminous representation of the fingerprint pattern to be generated. The second layer, strictly coupled with the first one, consists of a photodiode array (embedded in the glass) which is responsible for receiving the light emitted by the polymer and converting it into a digital image (Young et al., 1997). Some commercial sensors use just the first light-emitting layer for the image formation and a standard lens and CMOS for the image acquisition and digitization. In spite of great miniaturization, images produced by commercial scanners based on this technology are not yet comparable in quality with the FTIR images.

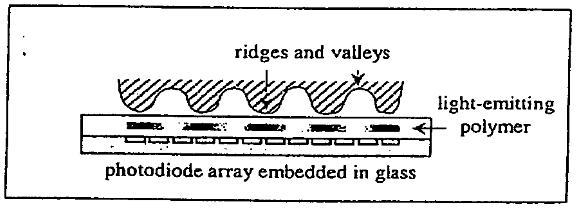


Figure 2.9. Electro-optical fingerprint sensor.

- *Direct reading*: A direct reading device uses a high-quality camera to directly focus the fingertip. The finger is not in contact with any surface, but the scanner is equipped with a mechanical support that facilitates the user in presenting the finger at a uniform distance. Such a device may overcome some problems such as periodically cleaning the sensor surface and may be perceived to be more hygienic, but obtaining well-focused and high-contrast images is very difficult.

Solid-state sensors

Although solid-state sensors (also known as silicon sensors) have been proposed in patent literature since the 1980s, it was not until the middle 1990s that these became commercially available (Xia and O'Gorman, 2003). Solid-state sensors were designed to overcome the size and cost problems which, at the time seemed to be a barrier against the deployment of fingerprint recognition systems in various applications. Actually, as discussed in the following, the cost of silicon sensors is not any lower than optical ones, especially when a very small sensing area is not acceptable. All silicon-based sensors consist of an array of pixels, each pixel being

a tiny sensor itself. The user directly touches the surface of the silicon: neither optical components nor external CCD/CMOS image sensors are needed. Four main effects have been proposed to convert the physical information into electrical signals: capacitive, thermal, electric field, and piezoelectric.

- *Capacitive*: This is the most common method used today within the silicon-based sensor arena (Tsikos (1982), Edwards (1984), Knapp (1994), Inglis et al. (1998), Setlak (1999), Lee et al. (1999), and Dickinson et al. (2000)). A capacitive sensor is a two-dimensional array of micro-capacitor plates embedded in a chip (see Figure 2.10). The other plate of each micro-capacitor is the finger skin itself. Small electrical charges are created between the surface of the finger and each of the silicon plates when a finger is placed on the chip. The magnitude of these electrical charges depends on the distance between the fingerprint surface and the capacitance plates (Tartagni and Guerieri, 1998). Thus fingerprint ridges and valleys result in different capacitance patterns across the plates.

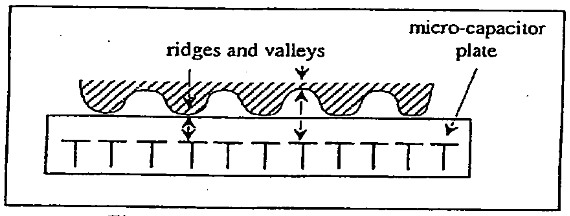


Figure 2.10. Capacitive sensing.

An accurate capacitance measurement is quite difficult to make and adjust, and each sensor has its own method to get enough sensitivity to make a difference between the ridges and the valleys. The capacitive sensors, like the optical ones, cannot be easily deceived by presentation of a flat photograph or printed image of a fingerprint since they measure the distances and therefore only a three-dimensional surface can be sensed.

A critical component of capacitive sensors is the surface coating: the silicon chip needs to be protected from chemical substances (e.g., sodium) that are present in finger perspiration. But a coating that is too thick increases the distance between the pixels and the finger too much, and the distinction between a ridge and a valley decreases, especially with poor quality fingers, where the depth of a valley is in the range of a micron. As a result, the coating must be as thin as possible (a few microns), but not too thin, as it will not be resistant to mechanical abrasion. Also, capacitive sensors sense the electrical field: electrostatic discharges (ESD) from the fingertip can cause large electrical fields that could severely damage the device itself. Therefore, proper protection and grounding is necessary to avoid ESD, chemical cor-

rosion, and physical scratches to the sensor surface (Thomas and Bryant (2000) and Setlak et al. (2000)).

An interesting property of capacitive sensors is the possibility of adjusting some electrical parameters to deal with non-ideal skin conditions (wet and dry fingers); a drawback is the need for frequently cleaning the surface to prevent the grease and dirt from compromising image quality.

- *Thermal*: These sensors are made of pyro-electric material that generates current based on temperature differentials (Edwards (1984) and Mainguet, Pegulu, and Harris (1999)). The fingerprint ridges, being in contact with the sensor surface, produce a different temperature differential than the valleys, which are away from the sensor surface. The sensors are typically maintained at a high temperature by electrically heating them up, to increase the temperature difference between the sensor surface and the finger ridges. The temperature differential produces an image when contact occurs, but this image soon disappears because the thermal equilibrium is quickly reached and the pixel temperature is stabilized. Hence a sweeping method (as explained in Section 2.5) may be necessary to acquire a stable fingerprint image. On the other hand, thermal sensing has some advantages: it is not sensitive to ESD and it can accept a thick protective coating (10 to 20 microns) because the thermal information (heat flow) can easily propagate through the coating.
- *Electric field*: In this arrangement, the sensor consists of a drive ring that generates a sinusoidal signal and a matrix of active antennas that receives a very small amplitude signal transmitted by the drive ring and modulated by the derma structure (subsurface of the finger skin). The finger must be simultaneously in contact with both the sensor and the drive ring. To image a fingerprint, the analogue response of each (row, column) element in the sensor matrix is amplified, integrated, and digitized.
- *Piezoelectric*: Pressure-sensitive sensors have been designed that produce an electrical signal when mechanical stress is applied to them. The sensor surface is made of a non-conducting dielectric material which, on encountering pressure from the finger, generates a small amount of current (this effect is called the piezoelectric effect). The strength of the generated current depends on the pressure applied by the finger on the sensor surface. Since ridges and valleys are present at different distances from the sensor surface, they result in different amounts of current. Unfortunately, these materials are typically not sensitive enough to detect the difference and, moreover, the protective coating blurs the resulting image. An alternative solution is to use micro-mechanical switches (a cantilever made of silicon). Coating is still a problem and, in addition, this device delivers a binary image, leading to minimal information.

Ultrasound sensors

Ultrasound sensing may be viewed as a kind of *echography*. It is based on sending acoustic signals toward the fingertip and capturing the echo signal (see Figure 2.11). The echo signal is used to compute the range image of the fingerprint and, subsequently, the ridge structure itself. The sensor has two main components: the transmitter, which generates short acoustic pulses, and the receiver, which detects the responses obtained when these pulses bounce off the fingerprint surface (Schneider and Wobschall (1991) and Bicz et al. (1999)). This method images the subsurface of the finger skin (even through thin gloves); therefore, it is resilient to dirt and oil accumulations that may visually mar the fingerprint. Good quality images may be obtained by this technology. However, the scanner is large with mechanical parts and quite expensive. Moreover, it takes a few seconds to acquire an image. Hence, this technology is not yet mature enough for large-scale production.

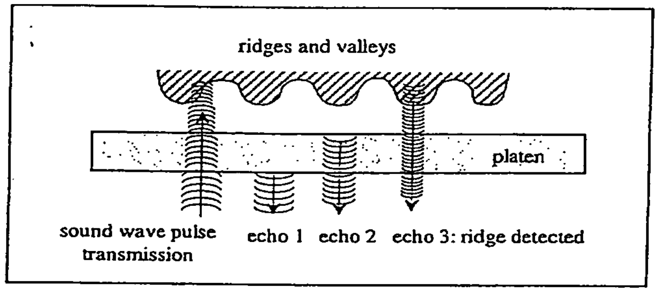


Figure 2.11. The basic principle of the ultrasound technique. Characteristic of sound waves is the ability to penetrate materials, giving a partial echo at each impedance change.

2.5 Touch versus Sweep

Most of the sensors available today use the *touch* method: the finger is simply put on the scanner, without moving it. The main advantage of this method is its simplicity: very little user training is required. On the other hand, this method has some drawbacks.

- Depending on the sensor technology and the operating conditions, the sensor can soon become dirty and must be cleaned periodically. Some people are reluctant to put their finger in the same place after someone else for hygiene reasons, especially if it looks dirty.

- A more-or-less-visible latent fingerprint remains on the sensor once the finger has been removed. In some cases, the sensor may be triggered to read this latent image as an input, and some countermeasures have to be adopted to prevent this.
- Rotation of the finger may be a problem for recognition: some matching algorithms do not accept large rotation (e.g., more than ±20°) of the finger. Generally, a guiding mechanism helps the finger to be always placed in the same way to avoid this.
- There is a strict tradeoff between the cost and the size of the sensing area. This is especially true for solid-state sensors, where the cost mainly depends on the area of the chip die. A larger die costs more due to fewer dies per wafer and lower yield; furthermore, large dies are more likely to include defects, resulting in a higher number of discarded chips. A typical capacitive touch sensor has a size of 15 mm by 15 mm, which is large for a chip.

With the main aim of reducing the cost, especially in silicon sensors, another sensing method has been proposed: to *sweep* the finger over the sensor. Since the sweeping consists of a vertical movement only, the chip must be as wide as a finger; on the other hand, in principle, the height of the sensor could be as low as one pixel: actually, since the finger movement speed is unknown and it can vary during the sweeping, the only way to reliably combine the different fingerprint readings (slices) is by requiring a certain degree of overlap between them. As a result, heights greater than one pixel are typically used. At the end of the sweep, a single fingerprint image has to be reconstructed from the slices. This could be done "on-the-fly" by combining the slices as they are delivered by the sensor (see Figure 2.12). In practice, using the sweeping technique, the size of the silicon sensor can be reduced by a factor of ten and the cost reduced commensurately (Xia and O'Gorman, 2003).

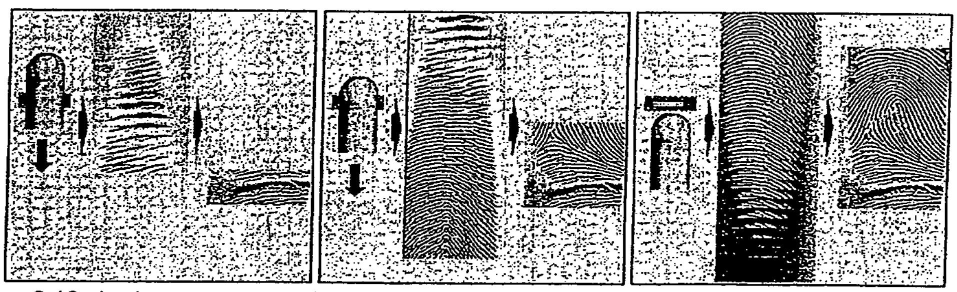


Figure 2.12. As the user sweeps her finger on the sensor, the sensor delivers new image slices, which are combined into a two-dimensional image.

The sweeping method was initially introduced in conjunction with thermal sensors, because sweeping was necessary to have a working "thermal" device. In fact, as discussed in

Section 2.4, the image vanishes very quickly because of the thermal equilibrium between the finger and the sensor. However, the equilibrium is continuously broken when sweeping, as ridges and valleys touch the pixels alternately, introducing a continuous temperature change. Nowadays, both the touch and sweep methods are being used with different sensor technologies. Optical scanners that use the sweeping method have also been proposed.

Unlike the touch devices, the sweep sensors always look clean since the finger itself cleans the sensor during usage, no latent fingerprint remains, and there is practically no rotation as the finger is always swept in the same direction (with the help of some mechanical guidance built in the scanner packaging). However, there are some drawbacks as well.

- The first times a novice user interacts with a sweep-based sensor, he may encounter some difficulties in performing the sweeping properly (i.e., without sharp speed changes, or discontinuity), and in general, it is less natural than using a touch-based device. In short, sweep sensors have a higher "habituation" period than touch sensors.
- The interface must be able to capture a sufficient number of fingerprint slices to follow the finger sweep speed. This may be difficult with interfaces with slow throughput, but does not constitute a problem with the available microprocessors and I/O interfaces.
- The full fingerprint image must be reconstructed from the slices; this process is time consuming and usually produces errors, especially in the case of poor quality fingerprints and non-uniform sweep speed.

Image reconstruction from slices

The sweep method allows the cost of a sensor to be significantly reduced, but requires reliable reconstruction to be performed. Figure 2.13 shows the block diagram of an algorithmic approach designed for a thermal sensor that delivers slices of 280×30 pixels. The main stages are as follows.

- *Slice quality computation*: For each slice, a single global quality measure and several local measures are computed by using an image contrast estimator; all successive stages are driven by these measures.
- *Slice pair registration*: For each pair of consecutive slices, the only possible transformation is assumed to be a global translation $[\Delta x, \Delta y]$, where the Δy component is dominant, but a limited Δx is also allowed to cope with lateral movements of the finger during sweeping. Finding the translation vector, or in other words, registering the two slices involves a search over the space of all possible translation vectors.
- *Relaxation*: When the quality of slices is low, the registration may fail and give incorrect translation vectors. Assuming a certain continuity of the finger speed during sweeping allows analogous hypotheses to be generated on the continuity of the translation vectors. The translation vectors' continuity may be obtained through a method

called relaxation (Rosenfeld and Kak, 1976) which has the nice property of smoothing the samples without affecting the correct measurements too much.

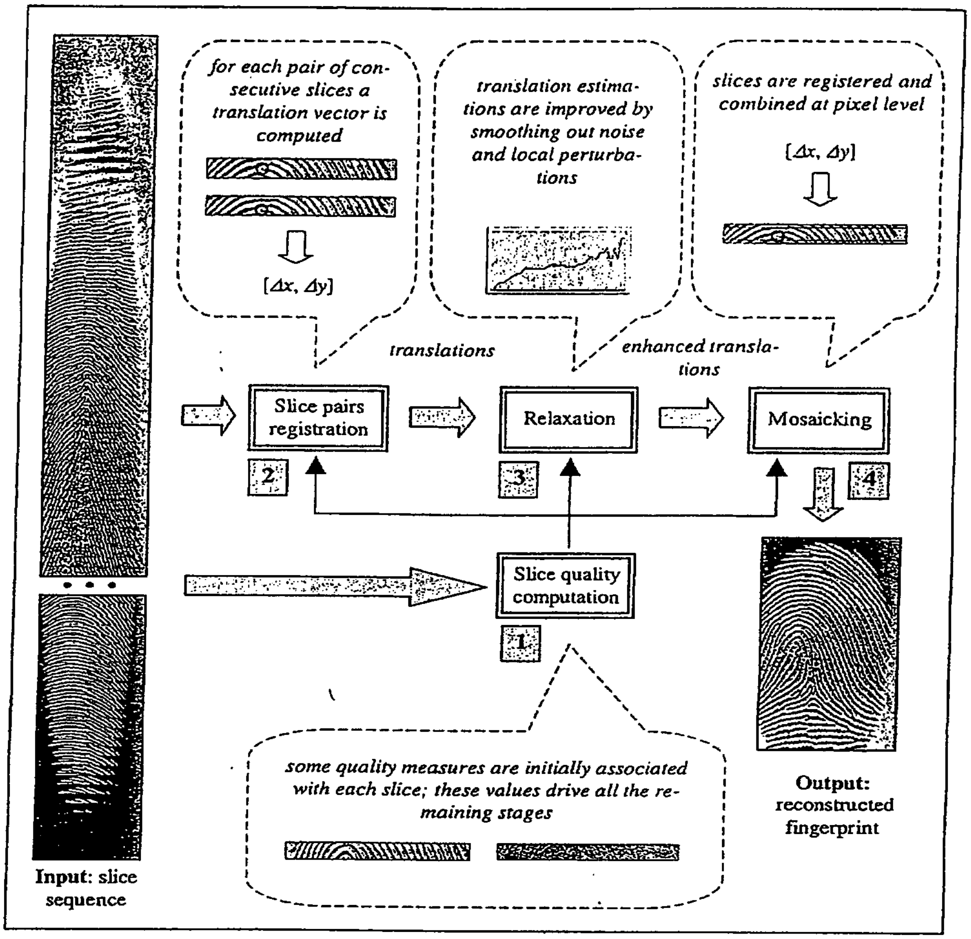


Figure 2.13. An algorithm for fingerprint reconstruction from slices. All the steps are performed sequentially on the whole set of slices. The output of the slice pair registration is a set of translation estimates that are globally enhanced by the relaxation step. These improved estimates drive the mosaicking phase in order to reconstruct the whole fingerprint image.

- *Mosaicking*: The enhanced translation vectors produced by the relaxation stage are used to register and superimpose the slices. Finally, each pixel of the reconstructed output image is generated by performing a weighted sum of the intensities of the corresponding pixels in the slices.

2.6 Fingerprint Scanners and their Features

Several fingerprint scanners, based on the sensing technologies surveyed in Section 2.4, are commercially available. Certainly, the main characteristics of a fingerprint scanner depend on the specific sensor mounted which in turn determines the image features (dpi, area, and dynamic range), size, cost, and durability. Other features should be taken into account when a fingerprint scanner has to be chosen for a specific application.

- *Interface*: FBI-compliant scanners often have analogue output (e.g., RS-170) and a frame grabber is necessary to digitize the images. This introduces an extra cost and usually requires an internal board to be mounted in the host. On the other hand, in non-AFIS devices, the analogue-to-digital conversion is performed by the scanner itself and the interface to the host is usually through a simple Parallel Port or USB connection.
- *Frames per second*: This indicates the number of images the scanner is able to acquire and send to the host in a second. A high frame rate (e.g., larger than 5 frames/sec) better tolerates movements of the finger on the sensors and allows a more friendly interaction with the scanner. It can also provide a natural visual feedback during the acquisition.
- *Automatic finger detection*: Some scanners automatically detect the presence of a finger on the acquisition surface, without requiring the host to continually grab and process frames; this allows the acquisition process to be automatically initiated as soon as the user's finger touches the sensor.
- *Encryption*: As discussed in Chapter 9, securing the communication channel between the scanner and the host is an effective way of securing a system against attacks. For this purpose, some commercial scanners implement state-of-the-art symmetric and public-key encryption capability.
- *Supported operating systems*: Depending on the application and the infrastructure where the fingerprint scanners have to be employed, compatibility with more operating systems, and in particular the support of open-source operating systems such as Linux, could be an important feature.

Table 2.1 lists some commercial scanners designed for the non-AFIS markets, whose cost is less than $200 US. Except for ultrasound scanners, which are not ready for mass-market applications yet, Table 2.1 includes at least one scanner for each technology.

	Technology	Company	Model	Dpi	Area (h×w)	Pixels
Optical	FTIR	Biometrika www.biometrika.it/eng/	FX2000	569	0.98"×0.52"	560×296 (165,760)
Optical	FTIR	Digital Persona www.digitalpersona.com	UareU2000	440	0.67"×0.47"	316×228 (72,048)
Optical	FTIR (sweep)	Kinetic Sciences www.kinetic.bc.ca	K-1000	up to 1000	0.002"×0.6"	2×900 (H×900)
Optical	FTIR	Secugen www.secugen.com	Hamster	500	0.64"×0.54"	320×268 (85,760)
Optical	Sheet prism	Identix www.identix.com	DFR 200	380	0.67"×0.67"	256×256 (65,535)
Optical	Fiber optic	Delsy www.delsy.com	CMOS module	508	0.71"×0.47"	360×240 (86,400)
Optical	Electro-optical	Ethentica www.ethentica.com	TactilSense T-FPM	403	0.76"×0.56"	306×226 (69,156)
Solid-state	Capacitive (sweep)	Fujitsu www.fme.fujitsu.com	MBF300	500	0.06"×0.51"	32×256 (H×256)
Solid-state	Capacitive	Infineon www.infineon.com	FingerTip	513	0.56"×0.44"	288×224 (64,512)
Solid-state	Capacitive	ST-Microelectronics us.st.com	TouchChip TCS1AD	508	0.71"×0.50"	360×256 (92,160)
Solid-state	Capacitive	Veridicom www.veridicom.com	FPS110	500	0.60"×0.60"	300×300 (90,000)
Solid-state (Thomson) =	Thermal (sweep)	Atmel www.atmel.com	FingerChip AT77C101B	500	0.02"×0.55"	8×280 (H×280)
Solid-state	Electric field	Authentec www.authentec.com	AES4000	250	0.38"×0.38"	96×96 (9,216)
Solid-state	Piezoelectric	BMF www.bm-f.com	BLP-100	406	0.92"×"0.63	384×256 (98,304)

Table 2.1. Some commercial scanners, grouped by technology. Technologies are presented in the order of Section 2.4, and within each technology, companies are listed in alphabetical order. The table reports for each scanner, the resolution, the sensing area, and the number of pixels. For sweep sensors, the vertical number of pixels varies depending on the length of the sweep, and therefore, cannot be determined a priori.

Figures 2.14 through 2.17 compare the same finger (a good-quality finger, a dry finger, a wet finger, and a poor quality finger, respectively) as acquired by using some of the scanners listed in Table 2.1.

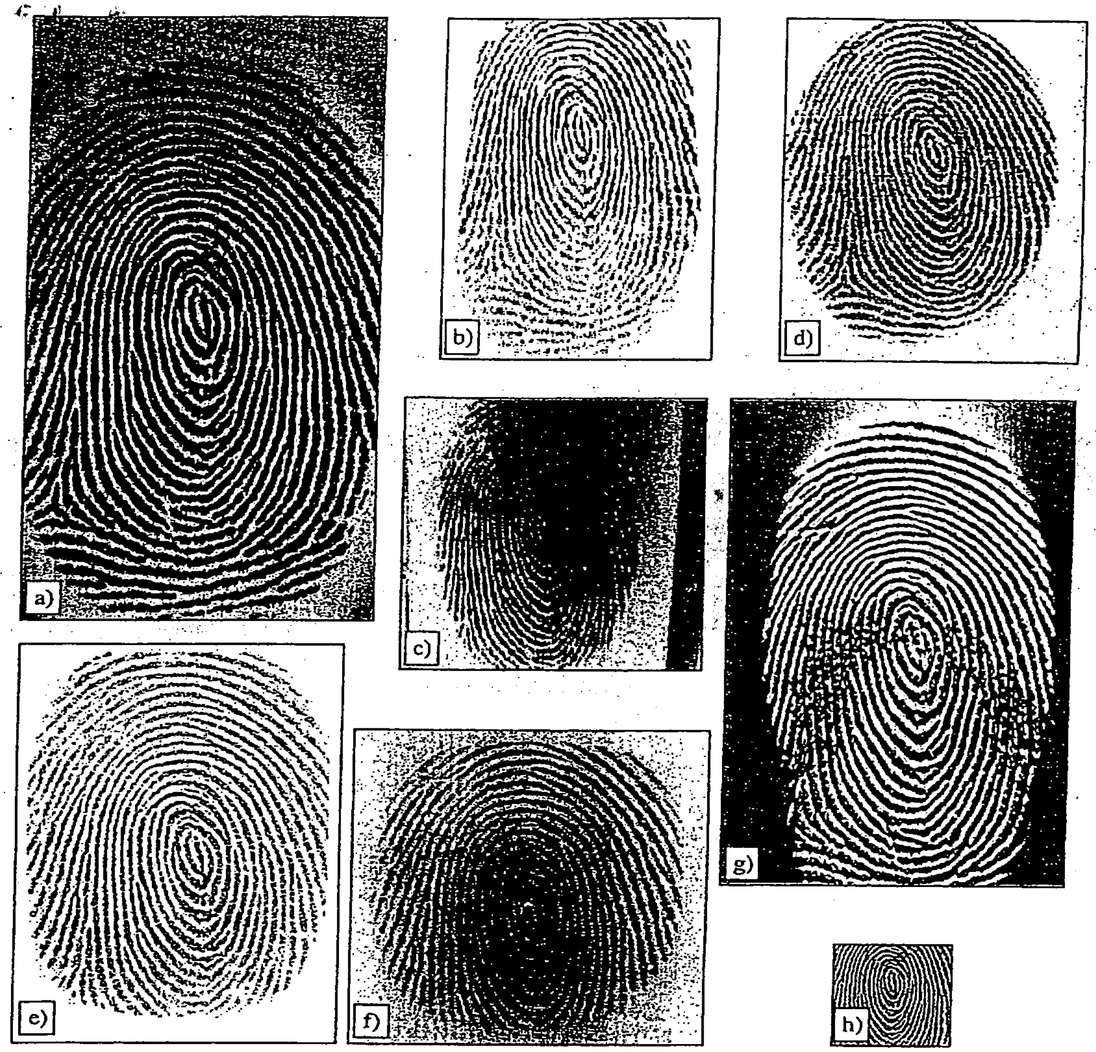


Figure 2.14. Fingerprint images of the same finger with ideal skin condition as acquired by different commercial scánners. Images are reported with right proportions: a) Biometrika FX2000, b) Digital Persona UareU2000, c) Identix DFR200, d) Ethentica TactilSense T-FPM, e) ST-Microelectronics TouchChip TCS1AD, f) Veridicom FPS110, g) Atmel FingerChip AT77C101B, h) Authentec AES4000.

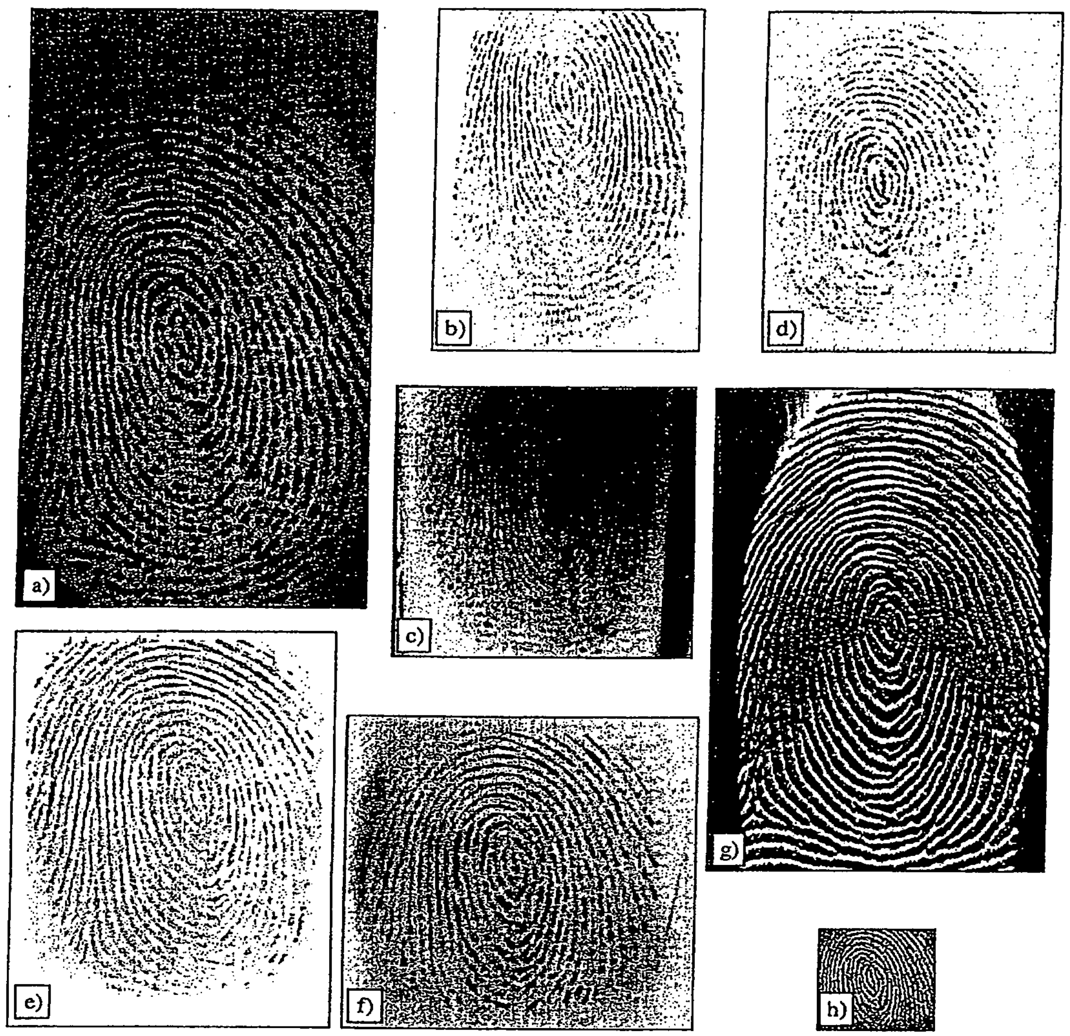


Figure 2.15. Fingerprint images of the same dry finger as acquired by different commercial scanners. Images are reported with right proportions: a) Biometrika FX2000, b) Digital Persona UareU2000, c) Identix DFR200, d) Ethentica TactilSense T-FPM, e) ST-Microelectronics TouchChip TCS1AD, f) Veridicom FPS110, g) Atmel FingerChip AT77C101B, h) Authentec AES4000.

Figure 2.16. Fingerprint images of the same wet finger as acquired by different commercial scanners. Images are reported with right proportions: a) Biometrika FX2000, b) Digital Persona UareU2000, c) Identix DFR200, d) Ethentica TactilSense T-FPM, e) ST-Microelectronics TouchChip TCS1AD, f) Veridicom FPS110, g) Atmel FingerChip AT77C101B, h) Authentec AES4000.

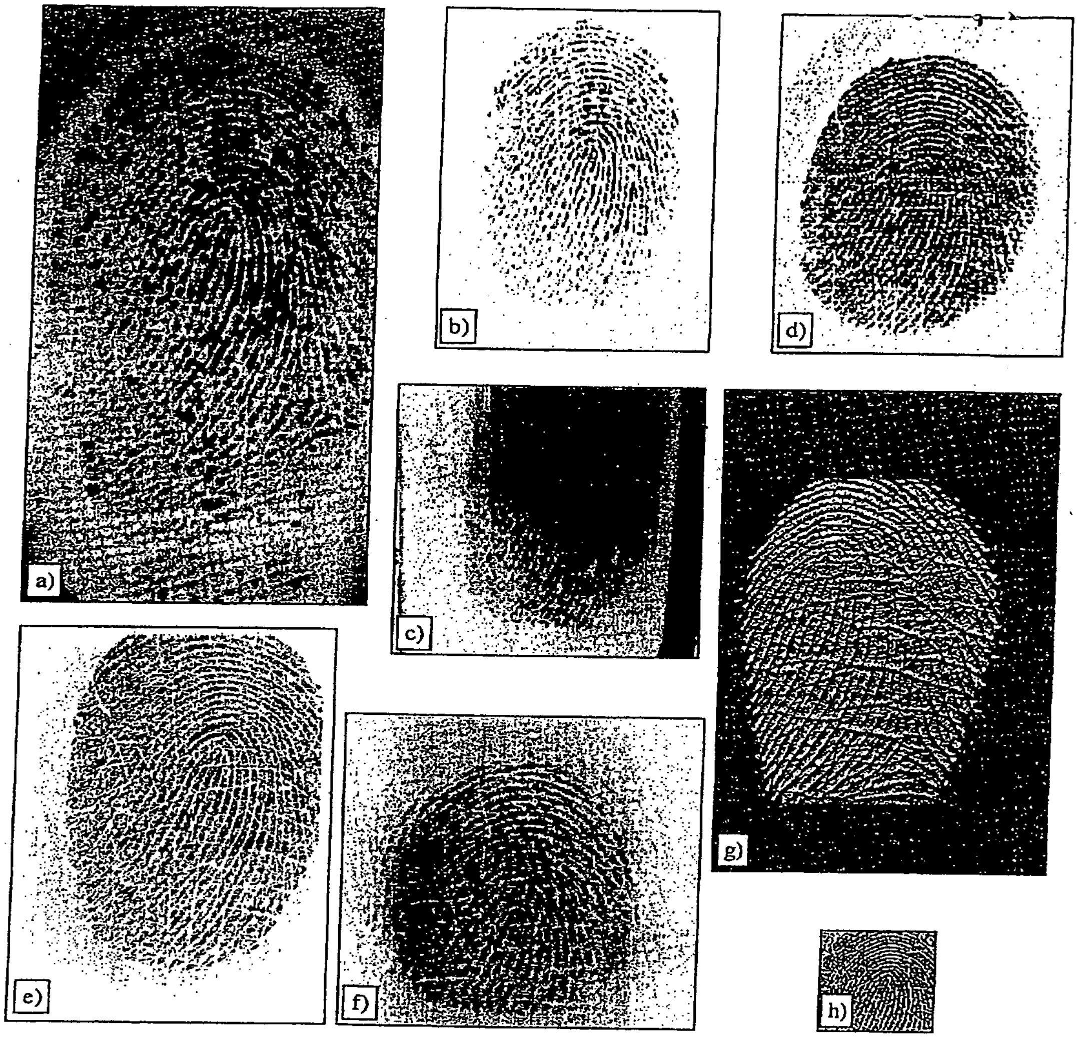


Figure 2.17. Fingerprint images of the same poor quality finger as acquired by different commercial scanners. Images are reported with right proportions: a) Biometrika FX2000, b) Digital Persona UareU2000, c) Identix DFR200, d) Ethentica TactilSense T-FPM, e) ST-Microelectronics TouchChip TCS1AD, f) Veridicom FPS110, g) Atmel FingerChip AT77C101B, h) Authentec AES4000.